Yielding of Coarse-Fine Particle Mixtures in Mineral Slurries

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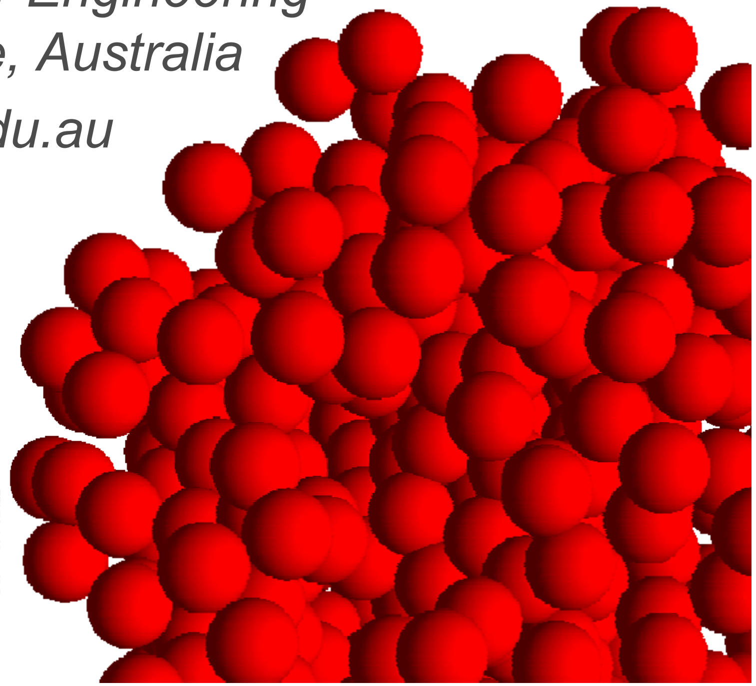

Particle Mixtures

Industries

- Water/Wastewater
- Algae for Biofuels
- Desalination
- Minerals Processing
- Ceramics
- Pulp and Paper
- Blood

and many more

Processes

- Flow
  Pumping and Mixing
- Dewatering
  Thickeners, Filters, Centrifuges

Theory & Methods

- Shear Rheology
- Compressional Rheology

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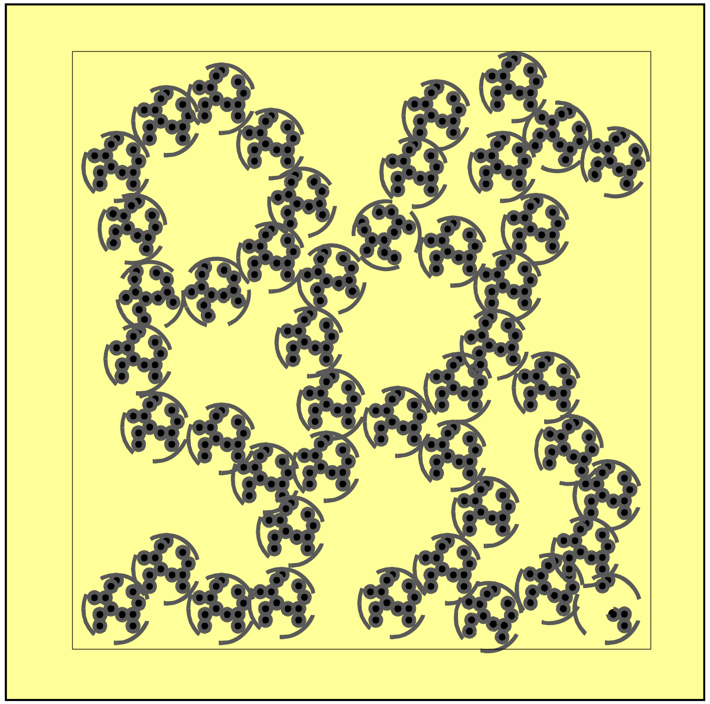
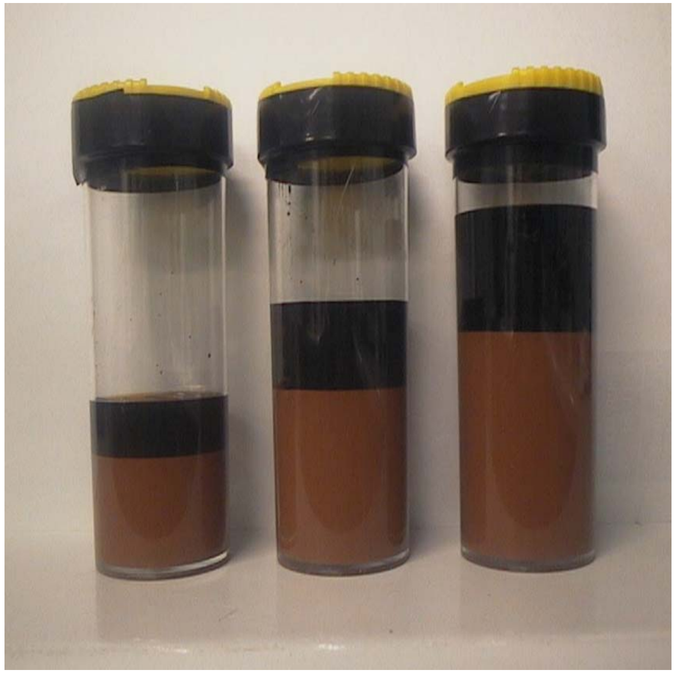
Material Properties

- Gel Point, ϕ_g
  - Minimum solids volume fraction at which the suspension forms a continuously networked structure that transmits its weight to the suspension below.

  - Can make an approximate measure from a batch settling experiment.





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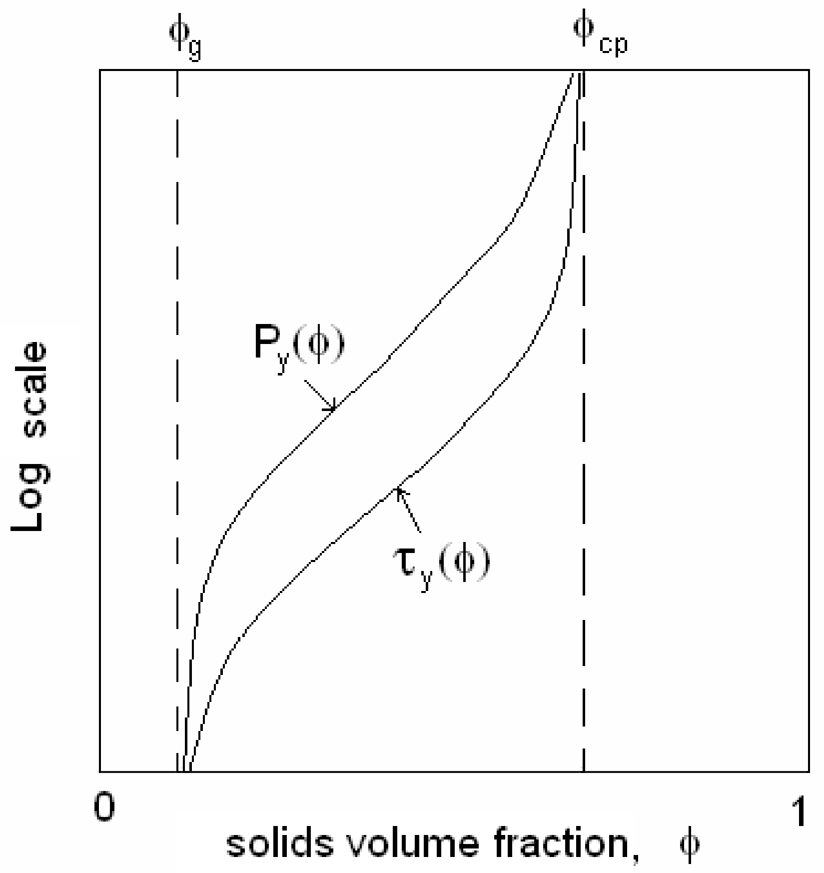
Material Properties

- Compressive Yield Stress, $P_y(\phi)$
  - Minimum compressive force required for a suspension to yield and compress.
- Shear Yield Stress, $\tau_y(\phi)$
  - Minimum shear force required for a suspension to yield and flow.



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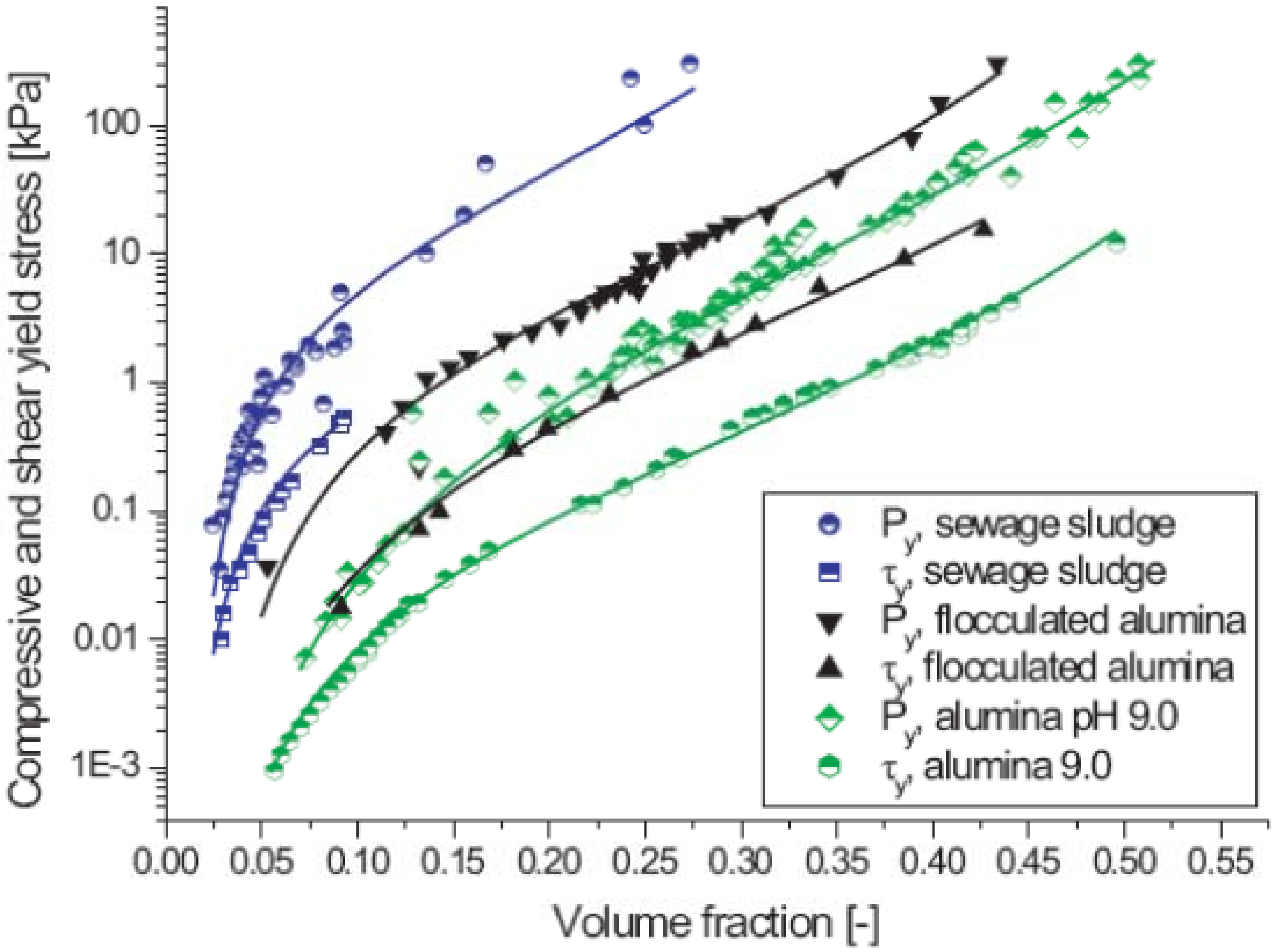
Material Properties



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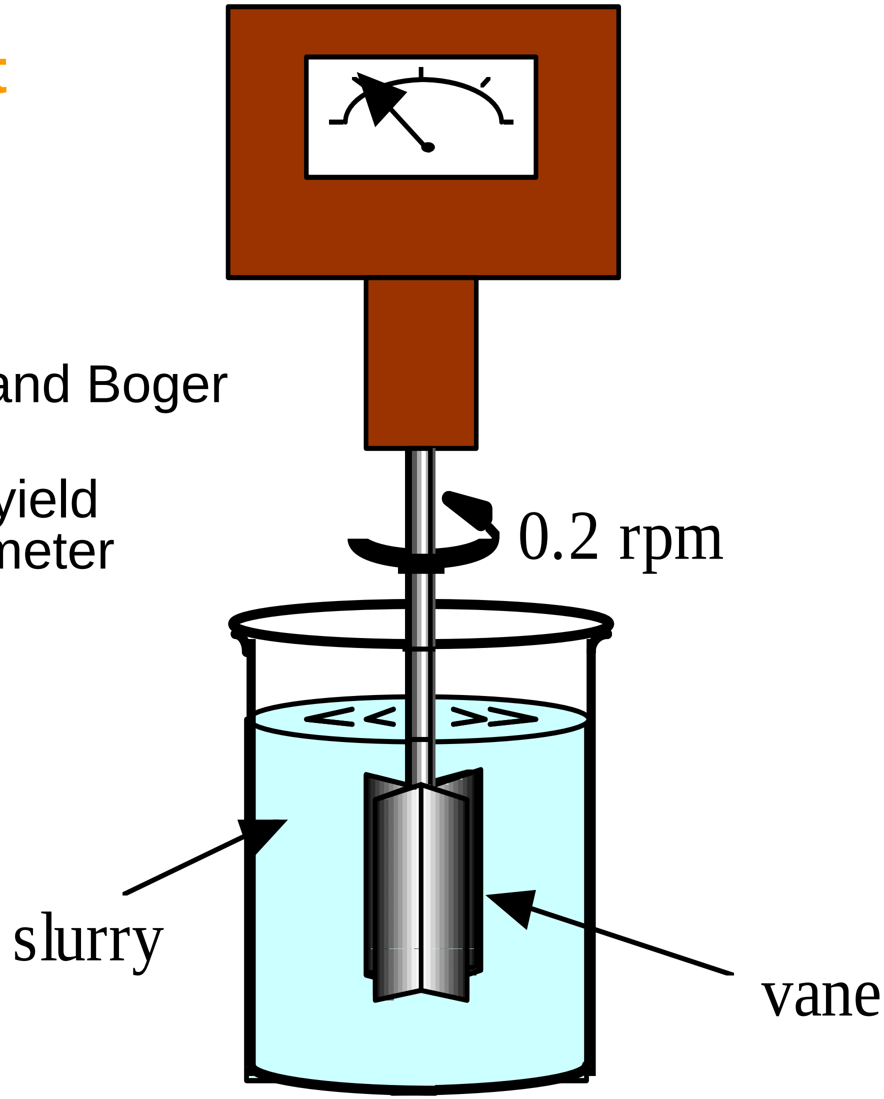
Yield Stress Measurement

- Vane technique
  - Developed by Nguyen and Boger 1983
  - measurement of shear yield stress via Haake Rheometer

$$\tau_y = \frac{T_{max}}{K_v}$$

$$K_v = \frac{\pi D_v{}^3}{2}\left(\frac{H_v}{D_v} + \frac{1}{3}\right)$$



- Nguyen QD, Boger DV, Journal of Rheology, 29 (1985) 335-347
- Pashias N, Boger DV, Summers J, Glenister DJ, Journal of Rheology, 40 (1996) 1179-1189

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Poly-disperse mixtures

Particle Size Distribution

- Bi-disperse mixtures
- Poly-disperse mixtures

Determination of bi-disperse mixture properties

- Measurements
  - Equilibrium Batch Settling
  - Yield stress measurement
  - Shear rheology measurements
- Model development

Development of an industrial tool for prediction of properties

- What is the minimum required information?

Materials - Solids

- Alumina
  - AKP-50 (4000 kg m^{-3}, d_{50} 0.14 μm, IEP 9.2)
- Calcium Carbonate
  - Omyacarb-2 (2700 kg m^{-3}, d_{50} 3.5 μm, IEP 8)
  - Omyacarb-40 (2700 kg m^{-3}, d_{50} 32.5 μm, IEP 8)
- Sand
  - AKP-50 (2600 kg m^{-3}, d_{50} 1083 μm)

Materials - Electrolyte

- Potassium Nitrate Solution
  - 0.01 M KNO_3 (aq) at pH 9.2

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Gel Point (Bi-disperse mixtures)

- **Measured**
  - *Vane technique*

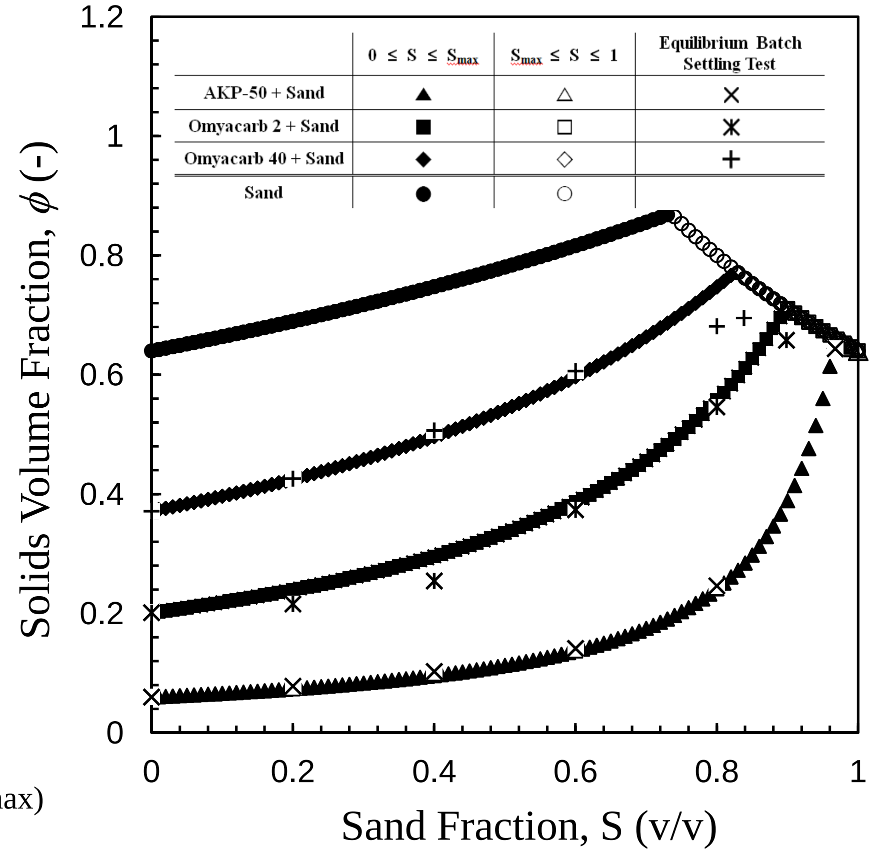
- **Predicted**
  - *Mixture solids volume fraction*

    $$\phi_{(mixture)} = \phi = \phi_{(fine)} + \phi_{(coarse)}$$

  - *Coarse fraction*

    $$S = \frac{\phi_{(coarse)}}{\phi_{(mixture)}} = \frac{\phi_{(coarse)}}{\phi_{(fine)} + \phi_{(coarse)}}$$

  - *Predictions*



$$\phi_{g\,(mixture)} = \frac{\phi_{g\,(fine)}}{1 - S + S\phi_{g\,(fine)}}, \quad 0 \le S \le S_{(max)}$$

$$\phi_{g\,(mixture)} = \frac{\phi_{cp\,(coarse)}}{S}, \quad S_{(max)} \le S \le 1$$

$\phi_g = \phi_{cp} = 0.64$ for coarse sand

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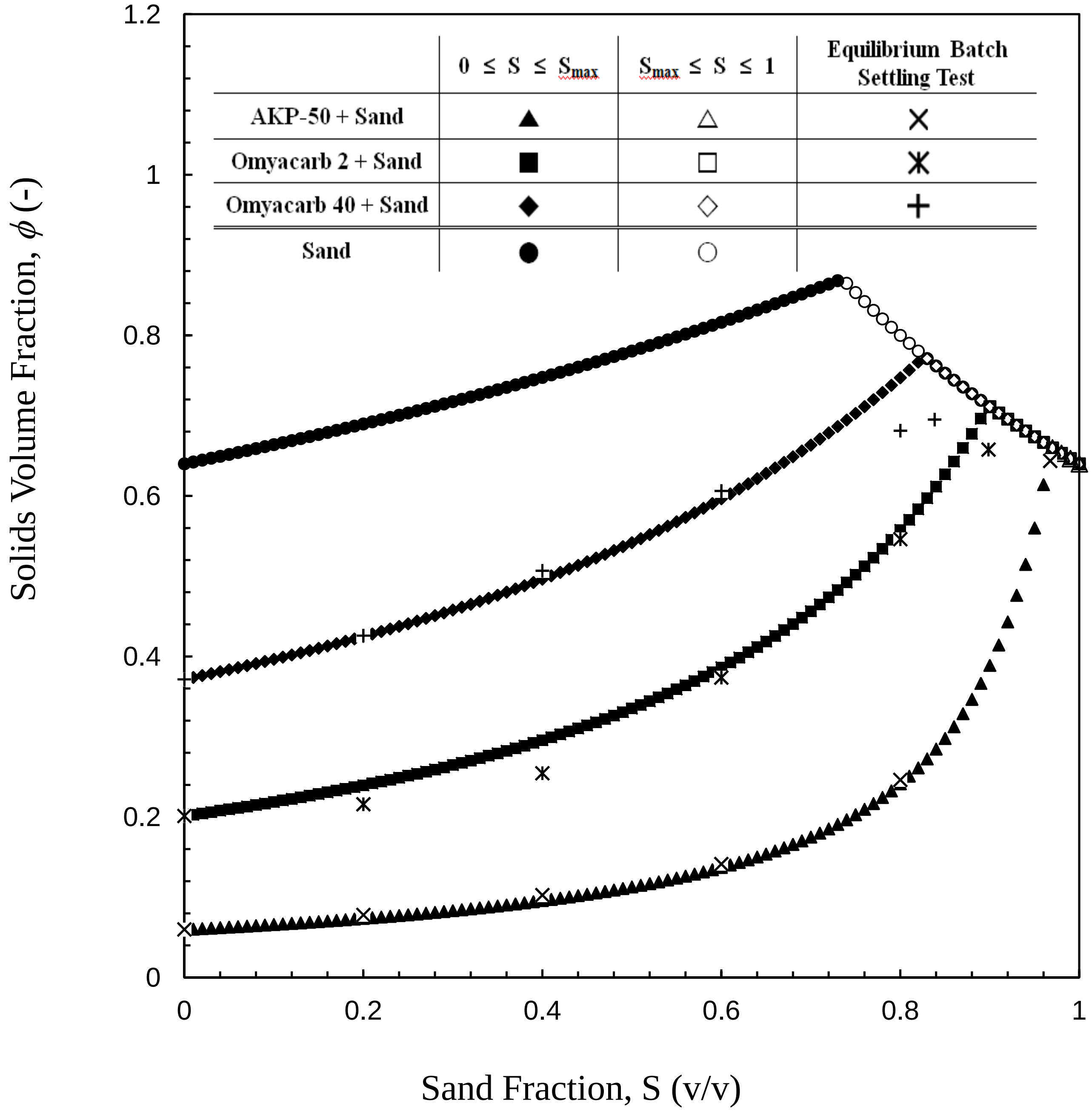

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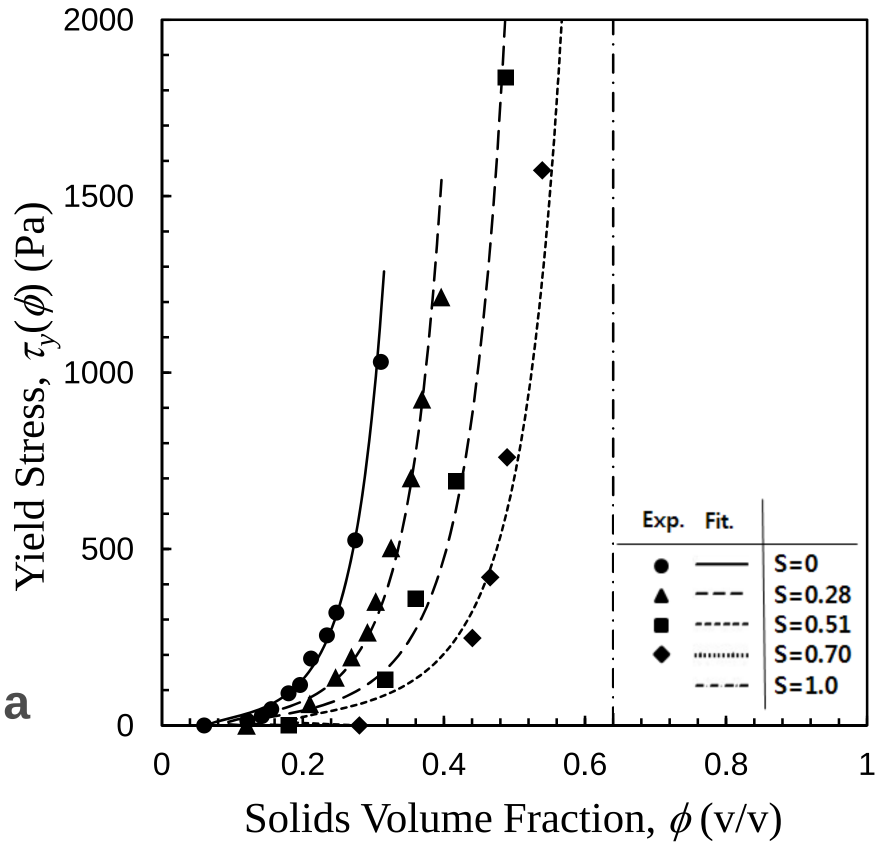
Yield Stress Constitutive Equation

- **Yield stress data is fitted to a constitutive equation:**

$$\tau_y = \left(\frac{a(\phi_{cp} - \phi)(b + \phi - \phi_g)}{(\phi - \phi_g)} \right)^{-k}$$

ϕcp is the close packing fraction
a, b and k are empirical fitting parameters

- **Gel point and close packing fraction predicted as described.**
- ***b* is assumed 0.002, while *a* and *k* parameter variation is determined as a function of sand fraction**



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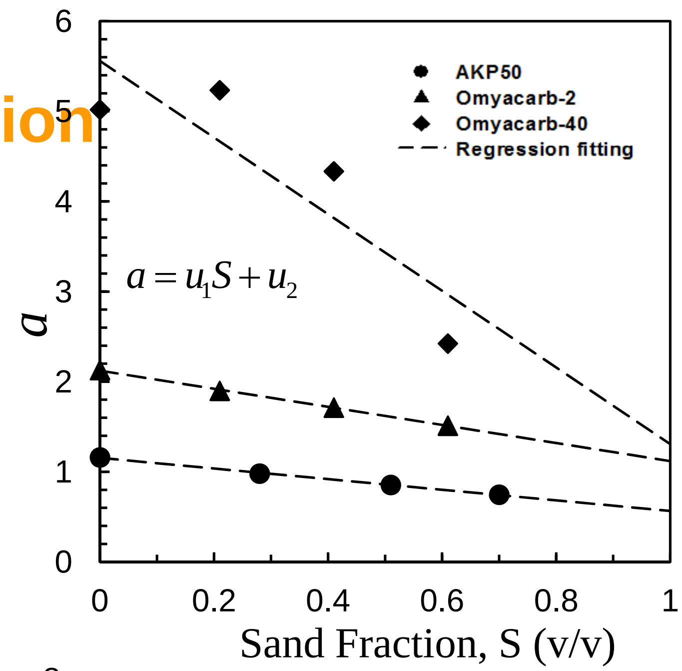

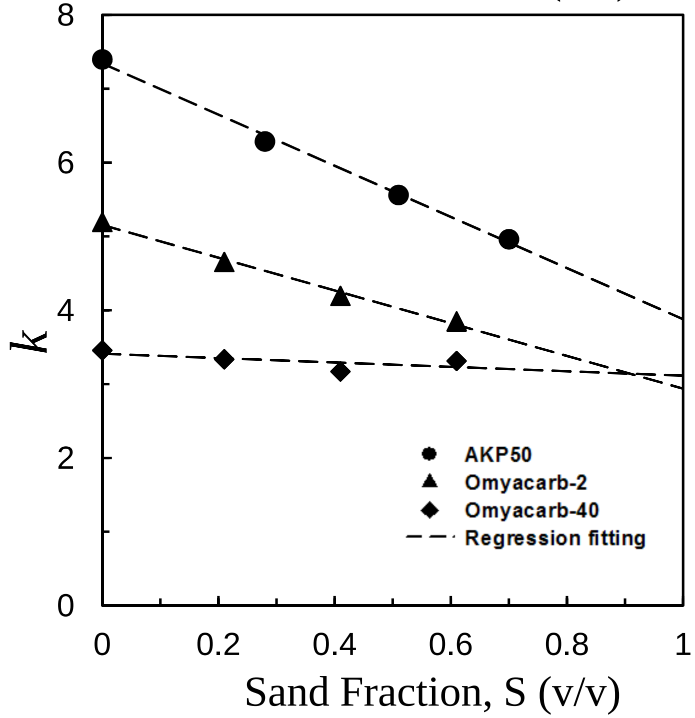

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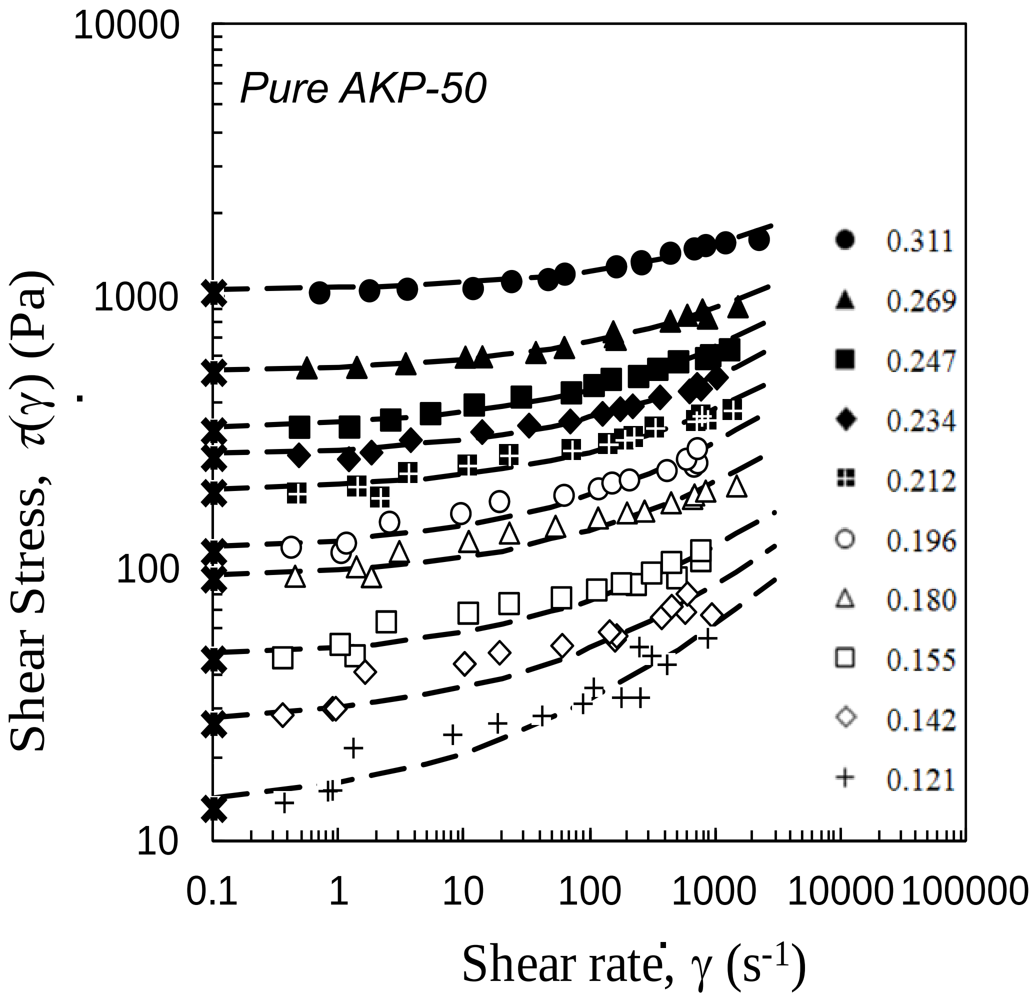
Herschel Bulkley model

- **Shear stress versus shear rate data also determined using the vane**
- **Data is fitted to Herschel Bulkley equation**

$$\tau = \tau_y + k\dot{\gamma}^{m}$$

- **Yield stress determined using prediction method**
- ***k* and *m* fitted to data**
  - ***Again, can determine variation of parameters with coarse fraction.***

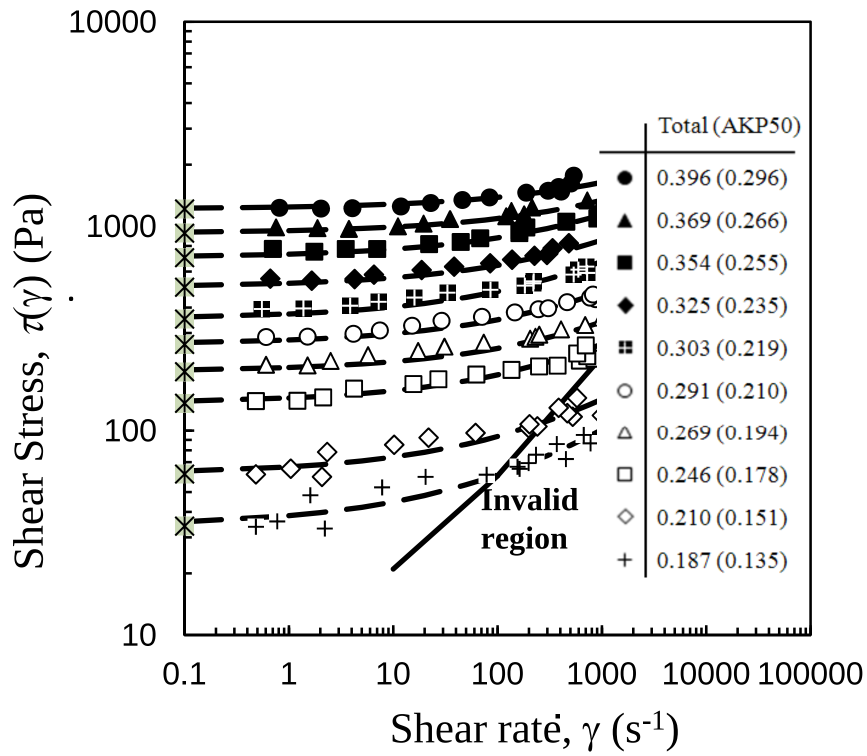


Sedimentation and Segregation

Particles settle due to gravity, even when the solids concentration is greater that the gel point.

Larger particles can settle faster.

- **Stokes Law**
  - **For isolated particles.**
  - **Gives maximum potential rate of segregation**



$$V_{coarse} = \frac{d_{coarse}^2 \cdot \Delta\rho \cdot g}{18\eta}$$

$$\Delta\rho_{fine,suspension} = \phi_{fine}\rho_{fine} + (1-\phi_{fine})\rho_{medium}$$

where V_{coarse} = the velocity of coarse particle
d_{coarse} = the diameter of coarse particle
$\Delta\rho$ = the density difference between coarse particle and fine particle suspension
g = the acceleration due to gravity
η = the viscosity of fine particle suspension at a given shear rate

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$\dot{\gamma}$

Conclusions

- Rheology of bi-disperse mixtures can be predicted:
  - ϕ_g and ϕ_{cp} variations can be predicted for bi-disperse mixtures
    - based on pure component properties,
    - requires significant particle size difference.
  - τ_y and P_y variations can be predicted
    - uses a constitutive equation.
  - τ versus $\dot{\gamma}$ variations can be predicted
    - using Herschel Bulkley parameters that vary with mixture composition.
  - Sedimentation and segregation can compromise measurements
    - Timescale of segregation must be longer than that of measurement.

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Further Work

- Polydisperse mixtures:
  - ϕ_g and ϕ_{cp} can be accurately predicted for mixtures of 3 or more components, provided that particle size differences are significant.
  - The challenge is to quantify the impact of particle size distribution overlap.
- Dewatering*:*
  - Compressive yield stress, $P_y(\phi)$ variations can be similarly be predicted for mixtures.
  - Settling rate predictions…

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